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Crop Rotation Effects on Soil Quality at Three Northern Corn/Soybean Belt Locations

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ABSTRACT

Do extended crop rotations that include forages improve soil quality and are they profitable? Our objectives were to determine (i) how crop rotation affected soil quality indicators, (ii) if those indicator changes were reflected in soil quality index (SQI) ratings when scored and combined using the Soil Management Assessment Framework, and (iii) how SQI values compared with profitability. Soil samples were collected from three long-term studies in Iowa and one in Wisconsin. Bulk density (BD), soil pH, water-stable macroaggregation, total organic C, total N, microbial biomass C, extractable P and K, and penetration resistance were measured. The indicator data were scored using nonlinear curves reflecting performance of critical soil functions (e.g., nutrient cycling, water partitioning and storage, and plant root growth). Profit was calculated by subtracting costs of production from potential income based on actual crop yields and the 20-yr average nongovernment-supported commodity prices. Extended rotations had a positive effect on soil quality indicators. Total organic C was the most sensitive indicator, showing significant measured and scored differences at all locations, while BD showed significant differences at only one location (Kanawha). The lowest SQI values and 20-yr average profit were associated with continuous corn, while extended rotations that included at least 3 yr of forage crops had the highest SQI values. We suggest that future conservation policies and programs reward more diverse and extended crop rotations, as is being done through the Conservation Security Program.

The dominant agricultural land use throughout the northern Corn/Soybean Belt became a 2-yr corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] rotation during the last half of the 20th century. This occurred for several reasons including simplicity and similar equipment requirements as farm size increased, commodity programs that emphasize short-term profit, public and private research and development efforts devoted to genetic improvement of corn and soybean, and increased food and industrial uses for both corn and soybean oils and various by-products (Karlen, 2004). It also coincided with major changes in the livestock industry that decreased demand for oat (*Avena sativa* L.) and alfalfa (*Medicago sativa* L.).

The merits of extended crop rotations that include forage or pasture crops have been debated for centuries (Karlen et al., 1994). Key benefits include increased C retention in the surface horizon and a more even distribution of labor needs and risk due to climate or market conditions than those involving only grain or fiber crops (Magdoff and van Es, 2000). Despite those benefits, the infrastructure developed and devoted to corn and soybean has resulted in a 500% increase in harvested area and 800% increase in soybean production between 1950 and 2003 (USDA-NASS, 2004). During that same period, oat production declined by 90%, and although hay production increased because of better yields, the land area devoted to it decreased more than 15%. Expansion of the simplified corn–soybean system has tremendous economic and world trade benefits because of the many products and materials developed from those crops, but what impact has it had on soil resources, water quality, biodiversity, wildlife corridors, and rural communities?

Some would argue that externalities of agricultural development are impossible to quantify and that the loss in crop diversity is no different now than during the 1950s when an average of 10 Wisconsin dairy farms went out of business each day for an entire decade (Apps, 1998). Others emphasize that to help shape a sustainable future, it is important to know where we are and how we got here (Flora, 2000; Randall, 2003).

Effects of extended crop rotations on soil quality have been discussed in general terms (Karlen et al., 1994) and specifically with regard to aggregate size distribution and stability (Kay, 1990; Robinson et al., 1994) and other indicators (e.g., yield, profit, N balance, etc.), but not with regard to soil quality per se. We acknowledge that soil quality assessment is in its infancy and that several valid concerns regarding its potential use and deficiencies have been raised (Letey et al., 2003; Sojka et al., 2003; Sojka and Upchurch, 1999). However, because shortsighted or improper soil and crop management decisions can lead to resource degradation and deleterious changes in soil function, tools and methods to assess and monitor soil quality are needed.

Soil quality effects of alternative vegetable production systems in northern California were quantified using the Soil Management Assessment Framework (SMAF) to combine various biological, chemical, and physical indicator measurements for an overall assessment (Andrews et al., 2002a, 2004). It was also used for an on-farm assessment of supplemental C management practices in California's Central Valley where it scored an established organic farming system higher than an adjacent conventional system (Andrews et al., 2002b). Recently,

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Abbreviations: BD, bulk density; C, corn; CSP, Conservation Security Program; ISU, Iowa State University; Om, oat/meadow; M, meadow; MB-C, microbial biomass carbon; Sb, soybean; SMAF, Soil Management Assessment Framework; SQI, soil quality index; TN, total nitrogen; TOC, total organic carbon; WSA, water-stable macroaggregation.

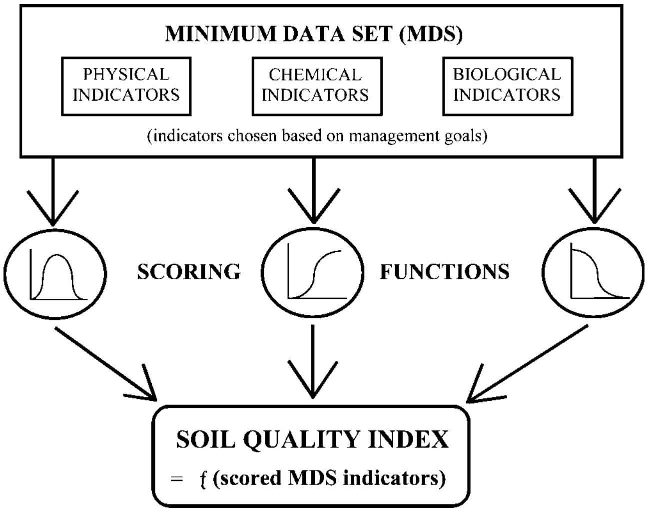

Fig. 1. Conceptual representation of the soil management assessment framework (SMAF).

the SMAF was used to evaluate long-term cropping system studies at eight locations in the Great Plains (Wienhold et al., 2006). They found that reducing tillage and the incidence of fallow combined with more diversified crop rotations improved soil function (i.e., supporting plant growth, providing a reservoir for essential plant nutrients, storing and purifying water as it passes through the soil, and providing a site for biological activity such as decomposing and recycling of plant and animal materials) throughout the Great Plains.

The SMAF focuses on dynamic soil quality, which refers to the effects of human use and management (e.g., crop rotations) on soil functions, in contrast to inherent soil quality, which is determined by the five soil-forming factors (Jenny, 1941) and emphasizes land use suitability (Andrews et al., 2004). Soil quality and its assessment is soil and site specific and depends on factors including its inherent capabilities, environmental influences such as temperature and precipitation, intended land use, and management goals. It is not intended to detract from the importance of soil taxonomy, but rather uses taxonomy as a foundation for assessment (Karlen et al., 2003). For example, optimum levels of soil organic matter (and all other properties) will differ depending on how and where the soil formed. Similarly, the soil functions, properties, and processes necessary for a road bed or to support a physical structure are not the same as those needed to produce crops. Furthermore, the functions and properties for benign land application of animal waste are not identical to those for maximum crop production—even within the same field or for the same crop. There is no single target or optimum soil quality standard for the U.S. or anywhere in the world (Andrews et al., 2004). Each site is independent and unique although high SQI values are always considered better than low values because they indicate better soil functioning.

Soil quality is thus based on a series of thresholds defined by limiting factors and user needs. Its assessment depends on indicators, defined as those soil properties and processes that have greatest sensitivity to changes in soil function. Indicators should correlate well with ecosystem processes, integrate soil properties and processes, be accessible to many users and sensitive to management and climate, and if possible, be components of existing databases (Doran and Parkin, 1996). Indicator groups or minimum data sets must be sufficiently diverse to represent biological, chemical, and physical properties and processes of complex systems. Currently, the SMAF has 11 scored indicators with several more (>20) being proposed, evaluated, or having preliminary scoring curves (Fig. 1). As evidenced by the initial case studies (Andrews et al., 2002a, 2002b, 2004), the SMAF uses quantitative laboratory analyses, provides site-specific interpretations, and can lead to a better understanding of how management affects a specific soil resource with respect to multiple endpoints that are outcomes driven by landowner/operator or societal goals (e.g., productivity and environmental quality). Proponents of SMAF suggest that it addresses most misgivings and misconceptions among those who have reservations regarding the soil quality concept (e.g., Sojka et al., 2003), but additional verification studies and subsequent improvements are needed.

Our objectives were to determine (i) how crop rotation affected soil quality indicators, (ii) if those indicator changes were reflected in SQI ratings when scored and combined using the SMAF, and (iii) how SQI values compared with profitability.

MATERIALS AND METHODS

Experimental Locations

Four long-term crop rotation studies (Fig. 2) located in north central [Iowa State University (ISU) Northern Research Farm near Kanawha, IA (42°56′ N, 93°48′ W)] and northeast Iowa [ISU Northeast Research Farm near Nashua, IA (42°57′ N, 92°32′ W)] and southwest Wisconsin [Lancaster Agricultural Research Station near Lancaster, WI (42°51′ N, 90°43′ W)] were selected for this study. The sites were originally established to evaluate crop rotation and N fertilization rate effects on crop yield (Mallarino and Pecinovsky, 2001; Mallarino and Rueber, 2001), soil N mineralization, retention,

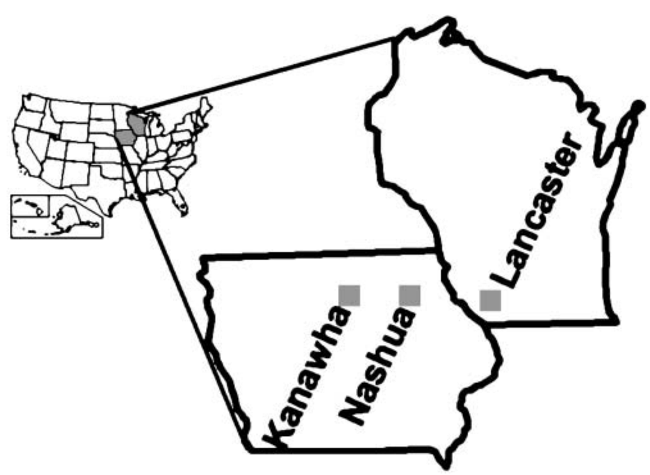

Fig. 2. Long-term crop rotation sites used for soil quality and economic assessments.

and availability (Vanotti and Bundy, 1994, 1995) and for an economic comparison between organic and conventional farming systems (Chase and Duffy, 1991). We chose to use a subset of plots at each site to test our hypotheses regarding crop rotation effects on soil quality and profit because of the long-term history and availability of detailed practices, inputs, and yields from each site.

Kanawha Cropping Systems Study

The Kanawha site was established in 1954 on a Webster (fine-loamy, mixed, super active, mesic Typic Endoaquolls) soil. The Webster series consists of very deep, poorly drained, moderately permeable soils formed in glacial till or local alluvium derived from till on uplands (USDA-SCS, 1989). The site is located on the Des Moines lobe, representing a relatively young landscape (≈12 000 to 14 000 yr) with 0 to 3% slope and mean annual air temperature and precipitation of 7.8°C and 762 mm, respectively (Prior, 1991). With appropriate drainage, the Webster soil is highly productive and is one of the most important row crop production soils in the Midwest, especially for corn and soybean.

Seven crop sequences have been evaluated since the experiment's inception although some changes have been made over time (Table 1). The meadow (forage legumes), whether seeded alone or with oat, has been a mixture of alfalfa and red clover (*Trifolium pratense* L.). No hay was harvested during the seeding year following oat harvest although in years when weed problems were severe, the oat was occasionally harvested for hay instead of grain. For rotations with 1-yr meadow, the legume mixture was plowed under during the fall of the same year. For rotations with 2 or 3 yr of meadow, two to four hay harvests were taken depending on seasonal weather patterns.

To accommodate all possible phases of the seven rotations and four fertilizer treatments, 224 plots (6.1 by 12.2 m) were established in 1954. Thus, for continuous corn (CC) [Rotations 1 and 7], there were four similar plots within each statistical block, and for Rotation 3 [corn–soybean (CSb)] there were two corn and two soybean plots within each block. There were some changes in N rate since the study was initiated, but since 1984, the annual rates were 0, 90, 180, and 270 kg N ha^{-1}. Except for Rotation 7, where N fertilizer was applied and incorporated in the fall, all N fertilizer treatments were applied in spring as urea and incorporated by disking. Tillage for all treatments consisted of moldboard plowing in fall, followed by disking as needed in spring before planting. Soil fertility samples were collected and analyzed every 4 to 6 yr, and uniform rates of P and K fertilizers were applied as needed to maintain optimum to high soil-test levels. Herbicides and cultivation were used for weed control as needed. Cultivars varied over time but were always improved selections developed for the region. Rotations 1, 2, 3, 5, and 6 (Table 1) were sampled and evaluated for this study.

Nashua Cropping Systems Study

The Nashua cropping systems study was initiated in 1979 on an area with Kenyon (fine-loamy, mixed, superactive, mesic Typic Hapludolls) and Readlyn (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) soils. The Kenyon series consists of deep, moderately well- and well-drained, moderately permeable soils formed on uplands in loamy sediments and the underlying glacial till with slopes ranging from 0 to 9% (USDA-SCS, 1995). The Readlyn series consists of very deep, somewhat poorly drained soils that formed in 35 to 66 cm of loamy sediments and the underlying firm glacial till. Readlyn soils are on slightly convex side slopes on uplands and have slopes ranging from 0 to 5%. Mean annual temperature and precipitation at this site are 8.1°C and 844 mm, respectively.

Table 1. Crop rotations at the various experimental sites in Iowa and Wisconsin used to evaluate soil quality and profitability effects.†

Treatment	Location and year of study			
	Kanawha, IA—Webster clay loam (cropping system study)			
	1954–1964	**1965–1977**	**1978–1983**	**1984–1997**
1	CC (spring N)			
2	CCCOm			
3	CSbCOm‡			CSb
4	CCCM	CSbCOm (76-cm rows)		
5	CCOmM			
6	COmMM			
7	CC (spring N)	CC (fall N)		
	Nashua, IA–Readlyn and Kenyon loam (cropping system study)			
	1979–1997			
1	CC			
2	CsCs			
3	CSb			
4	CCSb			
5	CCCSb			
6	CCOmM			
7	SbSb			
	Nashua, IA–Kenyon, Tripoli, and Readlyn soils (organic study)			
	1977–1980	**1981–1997**		
1	COmM (with manure)			
2	CC			
3	CSb			
4	–	COmM (without manure)		
	Lancaster, WI–Rozetta silt loam (crop sequence and nitrogen study)			
	1967–1976	**1977–1986**	**1987–1997**	
1	CC			
2	CSbCOmM			
3	CCOmMM			
4	CCCOmM	CCCMM		
5	CCCOmM	MM		
6	COmMMM	CCMM	CSb	
7	COmMMM	CCMM	CM	

† C, corn; Sb, soybean; Om, oat with legume seeding; M, meadow; Cs, corn silage.

‡ Row spacing was 102 cm (40 in) through 1977 and 76 cm (30 in) thereafter.

The Nashua site is located on the Iowan Surface, an area found in northeast Iowa and southeast Minnesota (Prior, 1991). The region is characterized by gently rolling hills with long slopes and low relief. Last glaciated over 500 000 yr ago, the glacial drift has been modified by erosion, especially severe during the Wisconsin glacial period (10 500 to 30 000 yr ago) when the region was tundra and the Des Moines lobe (Kanawha site) was being formed. Parent materials consist of eroded glacial till surfaces and alluvial and loess deposits. The Kenyon and Readlyn soils are highly productive and important for corn and soybean production.

The crop sequences (Table 1) varied depending on the frequency with which corn was planted, the harvest system for corn, and the presence of alternative grain (soybean or oat) or forage crops. The alfalfa was always seeded with oat. No hay was harvested during the seeding year, and three harvests were made in the second year. The crop sequence treatments were replicated three times (in a completely randomized, split-plot design). To grow all crops of each sequence every year, each crop sequence block was subdivided to accommodate each crop in the rotation. Thus, Treatments 1, 2, and 7, which were continuously cropped, have only one plot per block; Treatment 2 has two plots; Treatment 4 has three; and Treatments 5 and 6 each have four plots, for a total of 16 plots per block. The 16 plots are further divided into four smaller plots to accommodate the N fertilization treatments. Nitrogen fertilizer treatments were applied only to corn, using urea at rates of 0, 90, 180, and 270 kg N ha^{-1} and incorporated by disking immediately after application in the spring.

Tillage for all rotations consisted of fall chisel plowing and spring disking for corn or alfalfa residues and spring disking for soybean residues. Phosphorus and K fertilizers were applied as needed to maintain optimum soil-test levels. Herbicides and cultivation were used for weed control as needed. The type of herbicides used, as well as corn hybrid and soybean, oat, or alfalfa varieties, have varied over time but followed ISU recommendations. All crop rotations receiving either 0 or 180 kg N ha^{-1} fertilization rates were sampled for this study.

Nashua Organic Study

The Nashua organic study (Table 1) was established in 1977 on the same ISU research farm as the Nashua cropping systems study to demonstrate conventional and organic farming practices (Chase and Duffy, 1991). The initial study consisted of six plots: each phase of a corn–oat/meadow–meadow (COmM) rotation (three plots), continuous corn (one plot), and both phases of a corn and soybean rotation (two plots). The COmM rotation was fertilized with bovine manure, while the other two received ISU-recommended rates of fertilizer and pesticide as needed. Three additional plots were added in 1981 to accommodate another COmM rotation that did not receive any manure, pesticides, or commercial fertilizer.

Lancaster Cropping Systems Study

The Lancaster experiment was located on Rozetta (fine-silty, mixed, superactive, mesic Typic Hapludalfs) soil. The Rozetta series consists of very deep well-drained soils formed in loess on uplands (USDA-SCS, 1961). Permeability is moderate, and slopes range from 0 to 25% because the area was not glaciated 12 000 to 15 000 yr BP. Mean annual temperature and precipitation are 10.6°C and 914 mm, respectively. The site is located in the driftless area of Major Land Resource Area (MLRA) 105 found in southwest Wisconsin, southeast Minnesota, northeast Iowa, and northwest Illinois (USDA-SCS, 1981). The deep, rugged valleys and karst topography that characterize this 16.2 million ha region were carved into the sedimentary bedrock of a Paleozoic plateau by glacial runoff. The productive silt loam and loam soils were formed primarily from a deep loess layer overlying limestone, dolomite, sandstone, and shale bedrock (Prior, 1991). The steeply sloping land has very high erosion potential if not properly managed. Crop rotations, especially those with high residue production and including perennial crops like alfalfa, are important for comprehensive soil and crop management programs within this region.

The crop sequence and N study (Table 1) was initiated in 1967 as a cooperative experiment (NC-157) among the University of Illinois, ISU, University of Minnesota, and the University of Wisconsin to determine the crop production response to crop rotation on a typical upland soil within MLRA 105. A randomized complete block design with two replications of 21 treatments was established to test the rotation effect by having each phase of every rotation represented each year. The crop sequence plots were split to accommodate four N rate treatments, but only two (0 and 112 kg N ha^{-1}) were sampled for this study. Potassium and P fertilizer were applied at standard rates based on periodic soil testing (Mallarino and Rueber, 2001).

Sampling Strategy and Protocol

To control the overall size of this study, soil samples from the Kanawha, Nashua, and Lancaster cropping system sites were generally collected only from the plots planted to corn in 1997 and then only from two of the four N rates (0 and 90, 0, 180, or 0 and 112 kg N ha^{-1}, respectively). At Nashua and Lancaster, soil samples were also collected from the continuous soybean (SbSb) and continuous meadow (MM) plots. For the Nashua organic site (Table 1), samples were collected from the corn, soybean, and meadow phases of the rotations. However, this site was established as a nonreplicated demonstration project; therefore, pseudo-replication was achieved by dividing each treatment into three sections and collecting composite samples from each. The sampling strategy for each location resulted in data sets with an unequal number of replicates or pseudo-replicates (Table 2). Nevertheless, each set was still hypothesized to have completely random (i.e., sampling error) effects associated with the actual field replications, a hypothesis tested and verified as described in the statistical methods section.

A hand-probe with a 32-mm-diam. cutting tip was used to collect five soil samples from the 0- to 15-cm depth in each of the selected plots at all four sites during October and November, 1997. The samples were refrigerated until processing for BD, water-stable macro-aggregation (WSA), microbial biomass C (MB-C), total organic C (TOC), total N (TN), electrical conductivity (EC), and Mehlich III extractable nutrient concentrations. A hand-held cone penetrometer

Table 2. Field replications and pseudo-replications sampled at each of the long-term field sites used to evaluate soil quality and profitability effects of alternate crop rotations.

Long-term field site							
Kanawha		Lancaster		Nashua (cropping system)		Nashua (organic)	
Rotation†	Reps	Rotation	Reps	Rotation	Reps	Rotation	Pseudo-reps
CC	16	CSb	4	SbSb	6	CC	3
CSb	8	CC	4	CsCs	6	CSb	3
CCCOm	12	CSbCOmM	8	CC	6	SbC	3
CCOmM	8	CM	4	CSb	6	COmM+‡	3
COmMM	4	CCCMM	12	CCSb	12	OmMC+	3
		CCOmMM	8	CCCSb	18	MCOm+	3
		MM	4	CCOmM	12	COmM	3
						OmMC	3
						MCOm	3

† Crop designations: C = corn, Cs = corn silage, Sb = soybean, Om = oat with legume seeding, and M = meadow (alfalfa or alfalfa + red clover).
‡ + means with animal (bovine) manure.

with a 12.8-mm-diam. cone tip that had a 30° bevel was used to measure penetration resistance to a depth of 15 cm adjacent to where each soil sample was collected. Measurements were taken the same day as the soil was sampled, except at Kanawha where they taken 1 wk later because of rainfall. To minimize operator variability associated with penetration resistance measurements (Arshad et al., 1996), all five readings per plot at each location were taken by the same person.

Laboratory Analyses

Field-moist samples were weighed and then pushed through an 8-mm-diam- sieve. The soil water content was determined gravimetrically by oven-drying a subsample overnight at 105°C. Bulk density was estimated using the volume (121 cm^3) of soil associated with the five-core samples, the weight of soil, and the water content measurements (Arshad et al., 1996; Blake and Hartge, 1986). Aggregate stability (WSA) was assessed for 8-mm-sieved, air-dried samples and expressed as a percentage of the total soil that was greater than 250 μm in diameter after sieving in water (Cambardella and Elliott, 1993). Microbial biomass C was measured by fumigation and direct extraction with 0.5 M K_2SO_4 on 8-mm-sieved field-moist samples (Tate et al., 1988). Organic C in fumigated and nonfumigated extracts was measured using a Dohrmann DC-180 carbon analyzer[1] (Rosemount Analytical Services, Santa Clara, CA), and biomass C was calculated using a correction factor ($k = 0.33$) (Sparling and West, 1988).

Another subsample was pushed through a 2-mm-diam. sieve, air-dried, and stored at room temperature before analysis for TOC, TN, pH, and Mehlich III (Mehlich, 1984) extractable P and K. A subsample was pulverized and analyzed by dry combustion for TOC and TN using a Carlo-Erba NA1500 NCS elemental analyzer (Haake Buchler Instruments, Paterson, NJ). Phosphorous and K concentrations in the extracts were determined using an inductively coupled plasma–atomic emission spectrograph (ICP–AES). Soil pH was measured using a 1:2 soil-to-water ratio (Watson and Brown, 1998).

Soil Quality Assessment

The SMAF (Andrews et al., 2004) was used to calculate SQI values for each rotation at every experimental site. The measured indicator values were transformed with nonlinear scoring curves that had been constructed using CurveExpert v. 1.3 shareware (http://curveexpert.webhop.biz/; verified 25 Jan. 2006). The y axis for each curve provided a unitless value ranging between 0 and 1 reflecting the estimated performance of that indicator with regard to the critical soil functions. The x axis reflected the site-specific, expected range for each soil indicator. The shape of each scoring curve (Fig. 1) was either a bell-shaped curve ("midpoint optimum"), a sigmoid curve with an upper asymptote ("more is better"), a sigmoid curve having a lower asymptote ("less is better"), or some combination of curves linked with logic statements. For each study, inflection points of the scoring curves were adjusted for each site based on inherent environmental factors, such as organic matter class (taxonomic suborder), texture, climate, sampling time, mineralogy, region, slope, and analytical method for P (Andrews et al., 2004). The important soil functions (optimizing nutrient cycling, optimizing partitioning and storage of water, providing for good plant root growth, and providing filtering and buffering to minimize leaching and runoff of N and P) and their relationships to soil quality indicators were selected based on the literature and agronomic experience with extended crop rotations. Further information on the theory and development of the SMAF can be found in Andrews et al. (2004).

For this study, six soil quality indicators (BD, WSA, pH, TOC, MB-C, and P) were used to compute index values. Scoring curves for penetration resistance, extractable K, and TN are under development but have not been completed or rigorously tested. The scored indicator values were summed to create an additive index of soil quality for each rotation, assuming that higher scores (maximum value = 6.0) indicated better soil quality. An equal weighting (i.e., 1.0) was given to each indicator because there was no scientific or other reason (e.g., policy or regulatory) to justify variable weighting.

Profitability Assessment

Profit associated with the various crop rotations was computed by estimating the variable and fixed costs of production as outlined by Duffy and Smith (2002) and subtracting them from the potential income calculated using the actual yields for the 20-yr period before sampling and the average crop prices for those years from the NASS (National Agricultural Statistics Service) database. The potential impact of government support payments on cropping system choices was considered, but we chose to not use them for this analysis. Organic premiums were not used in the calculations associated with that study because the site was not certified. Actual costs for corn, corn silage, soybean, oat, and alfalfa production were gathered from several sources including annual Iowa Farm Business Association record summaries; production and cost data from the Economics, Agricultural and Biosystems Engineering and Agronomy departments at ISU; and a survey of selected agriculture cooperatives around the state. The cost estimates are representative of the average costs for medium and large farms in central Iowa and elsewhere in the state where yields and cultural practices are similar. Actual operations and input costs, including land and labor, were used if available, but if not, estimated costs were used (Duffy and Smith, 2002).

The owner/operator, family, or permanent hired personnel supply most labor on Iowa farms, so that cost, based on a wage rate of US \$8.00 h^{-1}, was treated as a fixed expense. The hours per crop-acre include not only the fieldwork but also time for maintenance, travel, and other activities related to crop production. The land charge was based on rent equivalent while equipment costs reflect a fleet consisting of both new and used machinery. Costs for machine operations were based on the 1998 Crop Production Practices Survey conducted by the Iowa Agricultural Statistics Service because those numbers reflected the economic situation when the soil samples were collected.

Statistical Methodology

This assessment of crop rotation (treatment) and N-rate (N_R) effects on soil quality and profitability used existing long-term field studies where the number of replicates or pseudoreplicates were unequal (Table 2). Therefore, each soil quality indicator variable for each location was examined separately with ANOVA procedures using SAS software (SAS Inst., 1990). First, a univariate distribution for each variable was determined using multiple exploratory tools including normality tests like the Shapiro-Wilk W statistic and symmetry transformation plots and statistics (Friendly, 1991). Appropriate transformations for meeting the ANOVA assumptions of normality and heteroskedasticity were performed before further analysis. All trans-

[1] Mention of trademark, proprietary product, or vendor is for information only and does not constitute a guarantee or warranty of the product by the USDA or Iowa State University or imply its approval to the exclusion of other products or vendors that may also be suitable.

formed data were converted back to original units for presentation in the tables and further discussion.

The next step for each variable was to examine the significance of the block as a random effect under the long-term design with a mixed-model procedure (Littell et al., 1996). No variable was found to have a significant block effect (data not shown), so the plots from each site were considered as samples in a completely randomized design. An ANOVA for each variable was computed with a two-way treatment structure and standard residual analyses. Planned contrasts among the various rotations were then evaluated.

RESULTS AND DISCUSSION

Bulk density, penetration resistance, WSA, pH, TOC, MB-C, and Mehlich III extractable P and K were evaluated to determine the long-term effects of various crop rotations and N fertilizer rates on soil quality at each location. These indicators were chosen to represent the physical, chemical, and biological condition of the soil resources, an important aspect of soil quality assessment (Karlen et al., 2004, 1997, 2001). Bulk density and penetration resistance were chosen to represent concerns associated with soil compaction; TOC and WSA served as indicators of soil structure, which influences many processes including infiltration, aeration, and nutrient cycling; pH, P, and K were indicators of soil chemical (fertility) status; and MB-C was an indicator of biological activity.

Penetration resistance (data not presented) showed few significant differences among the rotations at any of the sites, probably because the measurements were taken only within the top 15 cm of the soil profile. The average resistance for all rotations at all sites was between 100 and 200 kPa. Volumetric water content, which can significantly affect penetration resistance (Arshad et al., 1996), averaged 0.32, 0.31, 0.25, and 0.32 $cm^3\ cm^{-3}$ at the Lancaster, Kanawha, Nashua, and Nashua organic sites, respectively. There was a significant ($P \leq 0.02$) decrease in penetration resistance as volumetric water content increased at Lancaster, but overall predictability was low ($R^2 = 0.12$), and relationships at the other locations were not statistically significant.

Samples from the Kanawha site showed significant differences ($P \leq 0.1$) in BD, pH, TOC, and P (Table 3). Bulk density was approximately 7% higher in continuous row crop treatments (CC or CSb rotation) than in samples from corn grown as part of a more extended crop rotation. Soil pH was significantly lower for the COmMM rotation than for the continuous row crops (5.6 vs. 6.8), perhaps because long-term hay harvest had removed more bases (K, Ca, and Mg) than harvesting only the grain. Total organic C was 8.6 g kg^{-1} higher for the COmMM rotation reflecting less tillage and cycling C and N from the nodules and forage root system. Average extractable P concentrations were 9 mg kg^{-1} lower in rotations including multiple years of hay harvest (CCOmM or COmMM) than in continuous grain or rotations where oat was harvested but the legume was plowed down as green manure (CC, CSb, and CCCOm). We suggest greater P removal with the forage than with grain as the cause. Contrast analyses also showed significant differences between row crop treatments and extended rotations that included oat and forage crops (Table 3). Between the two sampled N rates, pH and P were both slightly lower (0.3 unit and 14 mg kg^{-1}, respectively) for the 80 kg ha^{-1} treatment than for the 0 N control, probably due to increased grain yield, nutrient removal, and acidification associated with higher N fertilizer rate.

Soil samples from the Nashua crop rotation site showed significant differences for WSA, pH, TOC, MB-C, P, and K (Table 4). Continuous corn grain and continuous soybean treatments had an average of 31% WSA, 18.8 g kg^{-1} TOC, and 500 mg kg^{-1} MB-C com-

Table 3. Indicator means, treatment contrasts, and N rate effects for long-term crop rotation treatments near Kanawha, IA.†

Rotation‡	BD	WSA	pH	TOC	MB-C	P	K
	g cm^{-3}	%		g kg^{-1}	mg kg^{-1}		
CC	1.14	44.8	6.73	33.4	800	60	244
CSb	1.11	45.2	6.84	32.7	816	43	233
*C*CCOm§	1.08	52.2	6.12	36.6	864	53	257
C*C*COm	1.04	56.0	6.21	34.5	862	63	268
CC*C*Om	1.07	45.5	6.81	34.5	872	48	238
*C*COmM	1.00	57.1	6.22	38.3	834	51	228
C*C*OmM	1.09	49.9	6.48	37.5	886	37	233
*C*OmMM	1.00	60.9	5.55	41.7	856	46	260
Treatment ANOVA–probability of > F	*0.0011*	*0.1680*	*0.0010*	*0.0031*	*0.8294*	*0.0433*	*0.4568*
Contrasts evaluated			Significance (probability of > *F*)				
CC vs. all others	0.0001	0.0399	0.0078	0.0065	0.1254	0.0166	0.9407
CSb vs. all others	0.0516	0.1269	0.0067	0.0073	0.4181	0.1605	0.2664
CC + CSb vs. all others	0.0002	0.0167	0.0003	0.0003	0.1210	0.6867	0.3628
*C*CCOm vs. *C*COmM vs. *C*OmMM	0.2714	0.4086	0.0390	0.0707	0.9300	0.4388	0.3621
*C*CCOm vs. C*C*COm + CC*C*Om	0.5155	0.8262	0.1859	0.3525	0.9678	0.8390	0.8404
*C*CCOm + C*C*COm vs. CC*C*Om	0.8705	0.2310	0.0318	0.6251	0.9022	0.2394	0.2052
*C*COmM vs. C*C*OmM	0.0370	0.3991	0.4243	0.7591	0.5300	0.1312	0.8132
N rate (kg ha^{-1}) effects	g cm^{-3}	%		g kg^{-1}	mg kg^{-1}		
0	1.08	50.4	6.50	35.8	836	57	250
80	1.06	52.2	6.24	36.4	862	43	240
Probability > |t|	*0.218*	*0.587*	*0.064*	*0.538*	*0.433*	*0.002*	*0.238*

† BD, bulk density; MB-C, microbial biomass carbon; TOC, total organic carbon; WSA, water-stable macro-aggregation.
‡ C, corn; Sb, soybean; Om, oat with legume seeding; M, meadow.
§ Italic indicates year of rotation for the corn crop sampled in autumn 1997.

Table 4. Indicator means, treatment contrasts, and N rate effects for long-term crop rotation treatments near Nashua, IA.†

Rotation‡	BD	WSA	pH	TOC	MB-C	P	K
	g cm^{-3}	%		g kg^{-1}	mg kg^{-1}		
CsCs	1.24	38.2	6.90	21.9	578	62	193
CC	1.33	31.4	6.70	18.8	477	47	127
Continuous soybean	1.26	30.2	6.98	18.9	522	70	159
CSb	1.17	38.4	6.96	20.2	544	58	160
*C*CSb§	1.25	37.7	7.07	18.7	577	57	164
C*C*Sb	1.28	39.2	7.02	19.3	585	55	178
*C*CCSb	1.18	44.0	6.95	19.8	562	32	187
C*C*CSb	1.34	46.9	6.85	20.2	577	55	175
CC*C*Sb	1.26	47.7	7.06	18.5	559	62	186
*C*COmM	1.20	42.6	6.76	20.7	609	61	191
C*C*OmM	1.26	43.8	6.92	22.5	679	60	190
Treatment ANOVA–probability of > F	*0.5945*	*0.0002*	*0.0751*	*0.0119*	*<0.0001*	*0.0738*	*0.0020*
Contrasts evaluated			Significance (probability of > *F*)				
Cs vs. C	0.2840	0.0879	0.1018	0.0101	0.0024	0.0147	<0.0001
Cs vs. SbSb	0.3592	0.7480	0.0261	0.8868	0.1600	0.0004	0.0416
C vs. SbSb	0.8755	0.0441	0.5362	0.0146	0.0850	0.2033	0.0333
All monocultures vs. CSb	0.1410	0.1137	0.3435	0.6824	0.4834	0.7638	0.9472
All monocultures vs. CCSb	0.8556	0.0440	0.0235	0.2759	0.0090	0.3030	0.2573
All monocultures vs. CCCSb	0.7261	<0.0001	0.2055	0.5791	0.0313	0.8873	0.0119
Monocultures vs. CCOmM	0.3646	0.0002	0.7970	0.0223	<0.0001	0.8824	0.0032
N rate (kg ha^{-1}) effects	g cm^{-3}	%		g kg^{-1}	mg kg^{-1}		
0	1.25	41.1	7.04	19.9	556	68	186
160	1.25	38.9	6.81	20.0	583	50	161
Probability > |t|	*0.927*	*0.180*	*<0.0001*	*0.940*	*0.053*	*<0.0001*	*0.0004*

† BD, bulk density; MB-C, microbial biomass carbon; TOC, total organic carbon; WSA, water-stable macroaggregation.
‡ C, corn; Cs, corn silage; Om, oat with legume seeding; M, meadow; Sb, soybean.
§ Italic indicates year of rotation for the corn crop sampled in autumn 1997.

pared with 43% WSA, 21.6 g kg^{-1} TOC, and 644 mg kg^{-1} MB-C in 4-yr rotations that included oat/meadow and meadow. Continuous corn for silage and various CSb rotations had WSA, TOC, and MB-C values that averaged 42%, 19.8 g kg^{-1}, and 569 mg kg^{-1}, respectively. Differences in soil properties ($P < 0.01$) between monocultures and the CCOmM rotation using contrasts confirm this crop rotation response. Similar to the Kanawha site, soil pH (6.8 vs. 7.0), extractable P (50 vs. 68 mg kg^{-1}) and K (161 vs. 186 mg kg^{-1}) at the Nashua cropping system site were all significantly lower in plots receiving 160 kg N ha^{-1} than the control (0 kg N ha^{-1}).

At the Nashua organic site, Mehlich III extractable P and K concentrations for the conventional, organic with manure, and organic without manure treatments averaged 60, 29, and 10 mg P kg^{-1} and 171, 119, and 95 mg K kg^{-1}, respectively (Table 5). Continuous corn and CSb rotation contrasts showed significant differences in soil pH (6.3 vs. 6.0), WSA (59.5 vs. 39.1%), TOC (37.6 vs. 24.1 g kg^{-1}), and MB-C (793 vs. 588 mg kg^{-1}). Conventional and organic plus manure contrasts showed lower pH (6.1 vs. 6.4) but higher P and K (60 vs. 29 mg P kg^{-1} and 171 vs. 119 mg K kg^{-1}) for the conventional management. Contrasts between the organic plus manure versus organic without manure showed the same pattern with lower soil pH (6.4 vs. 6.7) and higher P and K (29 vs. 10 mg P kg^{-1} and 119 vs. 95 mg K kg^{-1}, respectively). We suspect an important factor contributing to the low-fertility status within the organic treatments was that when the study was initiated in 1978, management may not have been as rigorous as if it had been overseen by an operator committed to organic agriculture. The

Table 5. Indicator means and treatment contrasts for conventional versus organic management treatments evaluated near Nashua, IA.†

Rotation‡	BD	WSA	pH	TOC	MB-C	P	K
	g cm^{-3}	%		g kg^{-1}		mg kg^{-1}	
CC	1.41	59.5	6.31	37.6	793	48	162
*C*Sb§	1.33	27.6	5.94	21.6	512	55	127
*Sb*C	1.29	50.7	6.12	26.6	663	78	225
*C*OmM (plus manure)	1.29	45.3	6.33	25.0	632	43	121
C*Om*M (plus manure)	1.32	43.0	6.72	30.9	856	24	129
COm*M* (plus manure)	1.45	49.4	6.27	29.5	829	20	108
*C*OmM (no manure)	1.41	45.2	6.65	25.7	708	18	92
C*Om*M (no manure)	1.30	41.9	6.81	28.3	731	16	96
COm*M* (no manure)	1.42	56.5	6.73	28.9	863	16	97
Treatment ANOVA–probability of > F	*0.7161*	*0.0237*	*<0.0001*	*0.0054*	*0.0476*	*<0.0001*	*0.0002*
Contrasts evaluated			Significance (probability of > *F*)				
CC vs. CSb rotation	0.2969	0.0057	0.0019	0.0002	0.0321	0.2017	0.9919
Conventional vs. organic plus manure	0.8665	0.9960	<0.0001	0.5264	0.0677	<0.0001	0.0018
Organic plus manure vs. organic w/o manure	0.7624	0.2378	<0.0001	0.6936	0.9664	<0.0001	0.0034

† BD, bulk density; MB-C, microbial biomass carbon; TOC, total organic carbon; WSA, water-stable macroaggregation.
‡ C, corn; Om, oat with legume seeding; M, meadow; Sb, soybean.
§ Italic indicates the crop being grown when sampled in autumn 1997.

conclusions reached in an economic analysis following the first 12 yr suggest this was a concern more than 7 yr before soil samples were collected for this study (Chase and Duffy, 1991).

Soil analyses from the Lancaster, WI site also showed significant differences in TOC, WSA, and MB-C among the various crop rotations (Table 6). Continuous corn plots had only 7.1% WSA compared with 16.5% WSA for continuous meadow, or an average of 12.5% WSA for the 4-yr CCOmM rotation. Total organic C and MB-C showed the same pattern among treatments, averaging 12.4, 15.8, and 14.1 g TOC kg^{-1} and 544, 757, and 640 mg MB-C kg^{-1}, respectively. The 2-yr CSb or CM, 4-yr CSbCOm, and 5-yr CCCMM rotations had WSA (8.7, 10.4, and 10.2% respectively), TOC (14.1, 14.3, and 14.1 g kg^{-1}, respectively), and MB-C (679, 615, and 621 mg kg^{-1}, respectively) that were also intermediate between the continuous corn and meadow (alfalfa). Extractable K levels were much lower for the continuous meadow (90 mg kg^{-1}) than for the average for the other rotations (147 mg kg^{-1}), presumably reflecting greater annual removal of K through the biomass (hay) than was being accounted for by the fertilization program. Contrasts between the continuous corn and the more diverse rotations showed significant differences for the TOC, WSA, MB-C, and extractable K. Comparisons between the two N fertilizer rates (0 and 100 kg ha^{-1}) showed a difference ($P < 0.02$) for BD (1.26 vs. 1.21 g kg^{-1}) but not for other indicators. This statistical difference, however, was considered insignificant from a practical perspective.

Among the three locations, there was a notable difference in the ratio of MB-C to TOC with the Iowa sites averaging 2 to 3% compared with 4 to 5% MB-C for the Wisconsin site. The Lancaster site also had lower TOC values than any of the Iowa sites, presumably because this site is located in the driftless area of MLRA 105. This area was not covered by ice during the most recent glacial period (≈12 000 to 15 000 yr BP) and is characterized by steep hills and deep, rugged valleys (USDA-SCS, 1981). Those inherent conditions presumably resulted in greater soil erosion before the establishment of the cropping system study, and therefore TOC values were much lower. During the 30 yr that the cropping systems studies were conducted, annual C inputs (i.e., substrate for the microbial communities) were presumably similar because all three sites were located at similar latitude (Fig. 2), with similar climatic conditions and similar crop sequences. Those similarities would thus account for the similar amounts of MB-C (i.e., ≈500 to 800 mg C kg^{-1} soil), but the ratios differ because of inherent differences in TOC.

Soil Quality Assessment

After evaluating individual indicator data from each experimental site, the values were scored using the SMAF (Andrews et al., 2004). This mathematical framework is sensitive to factors such as soil type, crop, and climate within and among studies and locations, with changes in the scoring curves based on inherent soil properties being derived by shifting inflection points and expected indicator ranges based on the best available information. For example, a TOC value of 20 g kg^{-1} for an Ultisol would receive a score of 1.0, indicating full functioning of any processes influenced by TOC. However, that same value (20 g kg^{-1}) in a Midwestern Mollisol would be scored below the threshold level (<0.5), indicating a degraded condition with probable impairment of soil functions influenced by TOC. Simi-

Table 6. Indicator means, treatment contrasts, and N rate effects for crop rotation treatments near Lancaster, WI.†

Rotation‡	BD	WSA	pH	TOC	MB-C	P	K
	g cm^{-3}	%		g kg^{-1}	mg kg^{-1}		
CC	1.28	7.1	6.55	12.4	544	31	140
CSb	1.26	8.9	6.54	14.2	667	27	134
CM	1.24	8.5	6.59	14.0	691	22	198
MM	1.24	16.5	6.37	15.8	757	22	90
*C*SbCOm§	1.18	11.9	6.56	15.0	649	19	122
CSb*C*Om	1.28	8.9	6.48	13.6	581	23	163
*C*CCMM	1.21	10.1	6.58	14.3	614	22	149
C*C*CMM	1.23	9.6	6.53	13.2	582	21	126
CC*C*MM	1.22	11.0	6.54	14.8	667	25	151
*C*COmM	1.26	12.2	6.47	13.4	608	21	134
C*C*OmM	1.19	12.7	6.53	14.8	672	22	154
Treatment ANOVA–probability of > F	*0.1854*	*0.0002*	*0.2474*	*0.0065*	*0.0013*	*0.3529*	*<0.0001*
Contrasts evaluated			Significance (probability of > *F*)				
CC vs. CSb	0.6629	0.0824	0.9218	0.0241	0.0027	0.3562	0.6587
CC vs. CM	0.2932	0.1653	0.6240	0.0497	0.0011	0.0431	0.0010
CC vs. MM	0.4198	<0.0001	0.0219	<0.0001	<0.0001	0.0552	0.0028
CC vs. extended rotations	0.0842	0.0002	0.6565	0.0047	0.0059	0.0102	0.8392
First-year C vs. second-year C	0.4295	0.9169	0.9079	0.7995	0.6574	0.9020	0.9111
First-year C vs. third-year C	0.8031	0.5695	0.6948	0.5361	0.2188	0.4187	0.8745
N rate (kg ha^{-1}) effects	g cm^{-3}	%		g kg^{-1}	mg kg^{-1}		
0	1.26	10.3	6.54	13.9	634	24	144
100	1.21	10.3	6.50	14.4	633	22	140
Probability > |t|	*0.017*	*0.975*	*0.169*	*0.151*	*0.930*	*0.172*	*0.577*

† BD, bulk density; MB-C, microbial biomass carbon; TOC, total organic carbon; WSA, water-stable macroaggregation.
‡ C, corn; Om, oat with legume seeding; M, meadow; Sb, soybean.
§ Italic indicates year of rotation for the corn crop sampled in autumn 1997.

larly, a soil-test P value of 150 mg kg^{-1} would receive a score of 1.0 for soils with 0 to 2% slope, approximately 0.75 for soils with 4 to 8% slope, and less than 0.1 for soils with more than 16% slope because of the potential for P loss through surface runoff or erosion on the more sloping soils.

The scoring curves used within the SMAF are adjusted for each indicator to make them site specific. When using the SMAF, information such as location, crop sequence, dominant soil series, when samples were collected, and how they were analyzed is entered by the user and used to automatically adjust the scoring curves. Thus, to model the associations among indicators, soil function, and controlling factors, one must have knowledge of (or make assumptions about) not only the appropriate curve shape (generally midpoint optimum, more is better, or more is worse, depending on the indicator's relationship to ecosystem function), but also the expected direction of change in curve inflections as major controlling factors change. For example, as temperature and precipitation increase, expected TOC values will decrease due to increased decomposition rates. This will result in a shift to the left (i.e., lower values get higher scores because that is the best possible for those inherent conditions) in the algorithm's inflection points (Andrews et al., 2004).

The final step associated with soil quality assessment is to combine all the available indicators into an overall SQI. This is an optional step since scored values for each indicator can and should be examined for their relative importance, but it offers the potential to integrate all of the indicator scores into a single, additive index value. The SQI is considered to be the overall assessment of soil quality. The integrated value, however, will be most relevant for evaluating dynamic or management-associated effects such as summarizing changes at the same location over time or comparing different management practices at a single field site because of the subtle differences in scoring curves based on inherent soil properties.

A comparison between the Kanawha and Nashua sites illustrates several points relative to soil quality assessments of long-term crop rotations (Tables 3 and 4). First, there is a distinct soil difference. Both have a loam texture, but TOC, WSA, and MB-C are all lower on the Till Plain soil (Nashua) than for the Des Moines lobe (Kanawha). Bulk density at Nashua was generally higher, reflecting more frequent tillage associated with row crops and lower TOC than at Kanawha.

Using the SMAF with Kanahwa data, BD and TOC showed scored differences ($P \leq 0.1$) among crop rotations with the lowest values being for the continuous corn (0.895 and 0.771) and CSb rotations (0.931 and 0.744), respectively. The 4-yr rotations with 1, 2, or 3 yr of oat/meadow or meadow had average values of 0.976, 0.978, and 0.990 for BD and 0.817, 0.854, and 0.926 for TOC, respectively. The nonscored data also showed differences ($P < 0.05$) for pH and P, but they were not significant when scored. Andrews et al. (2004) suggested that this pattern (i.e., significant unscored but nonsignificant scored values) occurs when measured differences are not significant with regard to soil function. With regard to soil pH and extractable P at the Kanawha site (Table 3), the scored differences were not significant because the values were within ranges acceptable for soil function, particularly crop productivity and environmental protection. When combined into an overall SQI, the continuous corn and CSb rotations also had lower values (5.50 and 5.53, respectively) than the 4-yr rotations, which averaged 5.75.

Table 7. Soil quality indicator scores and overall soil quality index (SQI) values for the long-term crop rotation and organic versus conventional management study near Nashua, IA.†

Rotation‡	BD	WSA	pH	TOC	MB-C	P	SQI
			Long-term crop rotation study				
CsCs	0.888	0.838	0.987	0.520	0.997	1.000	4.91
CC	0.802	0.762	0.993	0.381	0.983	1.000	4.60
SbSb	0.882	0.743	0.986	0.394	0.994	1.000	5.00
CSb	0.987	0.862	0.986	0.448	0.995	1.000	4.95
*C*CSb§	0.948	0.860	0.982	0.384	0.998	1.000	4.84
C*C*Sb	0.960	0.886	0.983	0.409	0.998	1.000	4.91
*C*CCSb	0.965	0.926	0.986	0.432	0.997	1.000	4.98
C*C*CSb	0.890	0.947	0.988	0.447	0.997	1.000	4.94
CC*C*Sb	0.863	0.933	0.982	0.373	0.997	1.000	5.46
*C*COmM	0.990	0.923	0.991	0.471	0.998	1.000	5.05
C*C*OmM	0.957	0.932	0.988	0.551	0.999	1.000	5.10
Treatment ANOVA–probability of > F	*0.3339*	*0.0003*	*0.1601*	*0.0146*	*<0.0001*	–	*0.8388*
			Organic versus conventional management study				
CC	0.778	1.000	0.999	0.953	1.000	1.000	5.73
CSb	0.916	0.694	0.996	0.515	0.993	1.000	5.12
SbC	0.951	0.943	0.998	0.729	1.000	1.000	5.63
*C*OmM (plus manure)	0.952	0.896	1.000	0.667	1.000	1.000	5.52
C*Om*M (plus manure)	0.918	0.928	0.984	0.826	1.000	0.982	5.64
COm*M* (plus manure)	0.690	0.968	0.982	0.817	1.000	0.975	5.43
*C*OmM (no manure)	0.791	0.934	0.996	0.692	1.000	0.974	5.39
C*Om*M (no manure)	0.727	0.964	0.980	0.768	1.000	0.949	5.39
COm*M* (no manure)	0.762	1.000	1.000	0.794	1.000	0.945	5.50
Treatment ANOVA–Probability of > F	*0.2425*	*0.0004*	*<0.0001*	*0.0046*	*0.0070*	*0.0050*	*0.1373*

† BD, bulk density; MB-C, microbial biomass carbon; TOC, total organic carbon; WSA, water-stable macroaggregation.
‡ C, corn; Cs, corn silage; Om, oat with legume seeding; M, meadow; Sb, soybean.
§ Italic indicates year of rotation for the corn crop sampled in autumn 1997.

Scored values for WSA, TOC, and MB-C showed significant differences in the long-term cropping systems study at Nashua (Table 7). Continuous soybean had the lowest WSA score (0.743), which agrees with conclusions reached by others (e.g., Power, 1990) that low residue production by soybean often reduces soil aggregation. Lower TOC scores were recorded for the continuous corn grain (0.381), continuous soybean (0.394), and 2-yr (0.384 for CCSb) or 4-yr (0.373 for CCCSb) rotations than for the other cropping systems, which (excluding continuous corn silage) averaged 0.460. The relatively high TOC score for the continuous corn silage treatment (0.520) was not anticipated but coincides with a higher observed value. The difference for MB-C score was caused by the slightly lower value (0.983) for the continuous corn grain treatment. However, MB-C scores were very high for all rotations at this site, and from a management perspective, this statistical result was not very important. We suggest that any score above 0.95 can be considered to be nearly optimum with regard to soil function.

Scored values for conventional and organic treatments at the Nashua organic study site showed differences ($P < 0.01$) for WSA, pH, TOC, MB-C, and P (Table 7). The conventional CSb rotation had much lower scored (and observed values) for WSA and TOC (0.694 and 0.515, respectively) than for the other rotations. Indicator scores for pH, MB-C, and P were different among the various rotations and management practices, but once again, all scores were very high, suggesting the statistical result was not important from a soil and crop management perspective. The overall SQI values showed no significant differences among conventional, organic plus manure, or organic without manure (5.49, 5.53, or 5.43, respectively) treatments. The SQI difference between continuous corn at the cropping system site and the organic site (4.60 vs. 5.73) is attributed to differences in TOC and WSA (Tables 4 and 5).

For the Lancaster site, TOC, WSA, and MB-C were different ($P < 0.01$), with continuous corn having lower scored values (0.353, 0.250, and 0.353, respectively) than the continuous meadow (0.586, 0.422, and 0.586, respectively) or than mean values associated with the 2-yr (0.397, 0.329, and 0.397, respectively) or 4-yr (0.453, 0.333, and 0.453, respectively) rotations (Table 8). The same response pattern was evident for the overall SQI (4.48, 4.54, 4.72, and 4.92) for the continuous corn, 2-yr rotations, 4-yr rotations, and continuous meadow, respectively.

Comparisons of ANOVAs for scored and nonscored indicator data can have four possible outcomes (Andrews et al., 2004). Differences among treatments may both be significant, nonsignificant, or alternating (i.e., significant nonscored values that are nonsignificant when scored with regard to soil function or nonsignificant means that are significant when scored because the measured differences occur at a very critical point with regard to soil function). Scored and nonscored indicators for our four sites show agreement ($P \leq 0.05$) at the Lancaster and Nashua organic locations (Table 9). For the Kanawha and Nashua cropping system sites, measured pH and Mehlich P showed significant differences, but scored values did not. This occurred because both pH and soil-test P were near optimum for crop production, and P levels were below those expected to have adverse environmental effects. These results were similar to those found in Northern Great Plains cropping systems (Wienhold et al., 2006), suggesting that extended rotations have a positive impact on soil quality and result in higher SQI values because of improved ecosystem functions.

Table 8. Soil quality indicator scores and overall soil quality index (SQI) values for the long-term crop rotation treatments near Kanawha, IA and Lancaster, WI.†

Rotation‡	BD	WSA	pH	TOC	MB-C	P	SQI
			Kanawha, IA				
CC	0.895	0.856	0.988	0.771	0.992	0.988	5.50
CSb	0.931	0.869	0.985	0.744	0.999	0.985	5.53
*C*CCOm§	0.972	0.929	0.995	0.844	0.999	0.995	5.74
C*C*COm	0.982	0.914	1.000	0.806	0.999	1.000	5.70
CC*C*Om	0.975	0.865	0.985	0.800	0.999	0.985	5.62
*C*COmM	0.990	0.982	0.995	0.860	0.999	0.995	5.82
C*C*OmM	0.965	0.920	0.992	0.847	0.998	0.992	5.73
*C*OmMM	0.990	0.996	0.980	0.926	0.998	0.980	5.89
Treatment ANOVA–probability of > F	*0.0681*	*0.2667*	*0.4892*	*0.0252*	*0.8961*	*0.4892*	*0.0050*
			Lancaster, WI				
CC	0.890	0.353	1.000	0.250	0.353	0.994	4.48
CSb	0.909	0.403	1.000	0.335	0.403	0.991	4.64
CM	0.926	0.390	1.000	0.322	0.390	0.992	4.63
MM	0.917	0.586	1.000	0.422	0.586	0.993	4.92
*C*SbCOm	0.963	0.478	1.000	0.375	0.478	0.979	4.80
CSb*C*Om	0.870	0.400	1.000	0.308	0.400	0.995	4.60
*C*CCMM	0.923	0.433	1.000	0.340	0.433	0.992	4.70
C*C*CMM	0.949	0.419	1.000	0.285	0.419	0.986	4.64
CC*C*MM	0.962	0.455	1.000	0.368	0.455	0.994	4.80
*C*COmM	0.888	0.486	1.000	0.295	0.486	0.974	4.64
C*C*OmMw	0.982	0.498	1.000	0.362	0.498	0.986	4.83
Treatment ANOVA–probability of > F	*0.2935*	*0.0002*	–	*0.0055*	*0.0002*	*0.4443*	*0.0031*

† BD, bulk density; MB-C, microbial biomass carbon; TOC, total organic carbon; WSA, water-stable macroaggregation.
‡ C, corn; Om, oat with legume seeding; M, meadow; Sb, soybean.
§ Italic indicates year of rotation for the corn crop sampled in autumn 1997.

Table 9. A comparison of ANOVAs for measured and scored indicators at three Iowa sites and one Wisconsin site.

	Kanawha		Lancaster		Nashua cropping systems		Nashua organic	
Indicator†	Measured	Scored	Measured	Scored	Measured	Scored	Measured	Scored
BD	**	‡	NS§	NS	NS	NS	NS	NS
WSA	NS	NS	**	**	**	**	*	**
pH	**	NS	NS	NS	‡	NS	**	**
TOC	**	*	**	**	**	**	**	**
MB-C	NS	NS	**	**	**	**	*	**
Mehlich P	*	NS	NS	NS	‡	NS	**	**

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.
† BD, bulk density; MB-C, microbial biomass carbon; TOC, total organic carbon; WSA, water-stable macroaggregation.
‡ Significant at $P \leq 0.10$.
§ NS, nonsignificant.

Profitability and Soil Quality Relationships

Without including government support payments, the calculated profit associated with almost all of the crop rotations was negative (Table 10). The most profitable rotation (COmMM at Kanawha) returned an average of \$74 ha^{-1} and had the highest SQI value (5.89 of a possible 6.0). The lowest SQI values were associated with the continuous corn treatments at all locations, generally because of the lower scores for BD, TOC, WSA, and MB-C (Tables 7 and 8). The high negative return ($-$\$130 ha^{-1}) associated with the continuous alfalfa at the Lancaster site, despite the relatively good SQI, was caused by lower-than-expected yields, possibly because of low soil-test K (Table 5.) Scoring curves for soil-test K have not been incorporated into the SMAF (Andrews et al., 2004) but are being developed.

The higher SQI associated with extended rotations involving meadow (forage crops) supports arguments that longer rotations may be more sustainable than current short-term agricultural practices (Randall, 2003). Perhaps with the help of federal incentive programs such as the Conservation Security Program (CSP) or other public and private research and development efforts, markets and uses for forage-based products will be developed to promote economic and environmental sustainability.

Table 10. Long-term profitability without government support payments and overall soil quality indicator scores for various crop rotations in the northern Corn and Soybean Belt.

Rotation†	20-yr average return	SQI
	US\$ ha^{-1}	
	Kanawha, IA	
CC	(232)‡	5.50
CSb	(23)	5.53
CCCOm	(173)	5.69
CCOmM	(14)	5.78
COmMM	74	5.89
	Nashua, IA	
CsCs	(132)	4.91
CC	(160)	4.60
SbSb (0 N)	42	5.00
CSb	2	4.95
CCSb	(32)	4.88
CCCSb	(58)	5.13
CCOmM	(24)	5.08
	Lancaster, WI	
CC	(143)	4.48
CSb	45	4.64
CM	(51)	4.63
MM	(130)	4.92
CSbCOmM	(78)	4.70
CCCMM	(84)	4.71
CCOmMM	(52)	4.74

† C, corn; Cs, corn silage; Om, oat with legume seeding; M, meadow; Sb, soybean.
‡ Returns in parentheses denote negative values.

CONCLUSIONS

Extended crop rotations that included at least 3 yr of forage crops in the northern Corn and Soybean Belt of the Midwestern USA had the highest soil quality rating when assessed using a minimum set of indicators (BD, WSA, pH, TOC, MB-C, and Mehlich extractable P). The lowest SQI values and 20-yr average returns (excluding annual government support payments) were associated with continuous corn at all locations. This was caused by low scores for BD, WSA, pH, TOC, and MB-C, indicating growing continuous corn in this region had negative effects on physical, chemical, and biological indicators of soil quality. We conclude that the SMAF is an effective tool for aggregating soil quality indicator data into index values that are effective for assessing alternative crop rotations or management (e.g., organic vs. conventional) systems. Based on these results, we also conclude that more diverse and extended crop rotations would improve the sustainability of agriculture throughout the region. To bring about this shift in cropping practices, future policy efforts should move away from commodity payments and toward more conservation incentives as is being done with the CSP.

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